Effect of Design Variables on the Reliability of Lead Free Area Array Connectors

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Abstract
As the use of area array connectors has become more widespread in electronic assemblies, the need to evaluate their reliability has increased. There is, however, limited information on how best to perform accelerated thermal cycle testing of area array connectors. Though specifications such as IPC-9701A can serve as useful guidelines in assessing second level reliability of these components, area array connector test vehicles are more complicated than test vehicles designed for testing traditional area array packages, as they require the use of daughter cards to allow the daisy chain to be completed and to properly emulate a real-world implementation of the connectors. While IPC-9701A can provide useful guidance in designing the motherboard, it offers no insight on the design of the daughter card, nor does it provide assistance in determining which version of a connector to test in cases where there are several variations within a connector product family. As accelerated thermal cycling tests can be expensive and time consuming, there is a need to assess the impact of these variables on the reliability of a connector to provide guidance in choosing the best way to test, and to assist in understanding how changes in the design between the test vehicle and the final product design may be expected to change the reliability.

The "Metro2" test vehicle was used to help generate data on these issues. In addition to providing manufacturability and reliability data on a selection of lead free area array connectors, three variations on one of the mezzanine connectors were studied to help assess the impact of design variables. The first comparison focused on the impact of changing the daughter card thickness from 0.062" to 0.093". Previous work on a tin/lead version of this connector indicated that the flexure of the 0.062" thick daughter card during thermal cycling played a role in the location of the solder joint failures observed, and as a result, it is expected that the increase in thickness may change the location of the failures and could also affect the reliability of the connector. The second comparison focused on the stack height of the connector. A 4mm stack height version of the connector was compared with a 6mm stack height version. The results of accelerated thermal cycling will be presented for the variations of this mezzanine connector along with the failure analysis results. Results will also be compared to those obtained on the tin/lead version of the same connector.

Introduction
Area array connectors have proven to have many benefits in electronic assemblies. In addition to offering potentially superior signal integrity and denser signal routing than many through hole or press fit connectors, area array connectors offer the possibility to reduce or eliminate the need for wave soldering or press fit assembly, as they are attached during the SMT process. Like conventional BGA components, they benefit from self centering of the area array on the pads during the reflow process, and are therefore more forgiving of slight misplacement and can have excellent assembly yields. However, area array components are also subject to the type of solder joint fatigue issues that are inherent to other SMT components, and their reliability needs to be assessed prior to use in volume manufacturing. Standardization of reliability testing of SMT components has been in place for some time, with specifications such as IPC-9701A[1] providing guidelines for test vehicles and test conditions for assessing the reliability of surface mounted components. Although these specifications provide some useful guidelines for the reliability testing of area array connectors, they do not adequately address all the unique characteristics of connectors. One significant gap is in the area of test vehicle design. Many connectors, such as mezzanine connectors and backplane connectors require two mated test vehicles to mimic their end application. No standardized guidelines exist for the design of a daughter card or backplane suitable for testing area array connectors, and relatively little is yet known about the effect of changing design parameters, such as thickness, of these boards on the reliability of these connectors. Another gap is in determining how certain design features of the connector itself, such as stack height, will impact the reliability. This lack of data may result in the worst case in reliability testing every variation of a connector that is offered, which is clearly unrealistic in the long term. The effect of these types of variations must be better understood to develop guidelines for what connector design changes require re-testing, and which can be considered at least as reliable as versions for which reliability testing has already been performed.

The "Metro2" test vehicle aimed to generate data to help close some of these gaps by looking at three different configurations of a single connector type in one test. This test vehicle is a follow on to the original "Metro" test vehicle, which studied the reliability of five connector families, and has been reported on previously[2-3]. The "Metro" test vehicle was a tin/lead assembly, with tin/lead area array components. "Metro2" used lead free area array connectors, and was a fully lead free assembly. Both of these test vehicles featured an area array mezzanine connector, and in comparing the reliability testing results from these test vehicles, it was possible to assess the effect of conversion to lead free, of daughter card thickness, and of connector stack height on the reliability of the connector.

Component

The component discussed in this paper is an area array mezzanine connector, and is shown in Figure 1. It has 240 I/O on a 1.27mm pitch, and has eutectic tin/lead balls when used on the "Metro" test vehicle, and lead free SAC405 balls when used on the "Metro2" test vehicle. It has been referred to in previous publications on the "Metro" and "Metro2" test vehicles as Mezzanine Connector B[2-4].

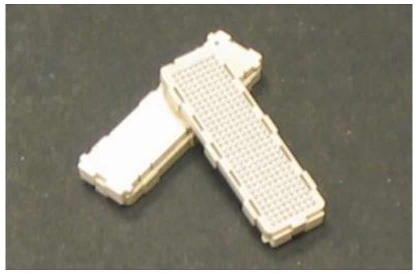

Figure 1 - Area Array Mezzanine Connector

Test Vehicles

Both test vehicles were designed to assess the manufacturability and reliability of several components in additions to Mezzanine Connector B. The original "Metro" test vehicle tested one tin/lead version of the connector. The "Metro" test vehicle is shown in Figure 2 with the Mezzanine connector B daughter card circled.

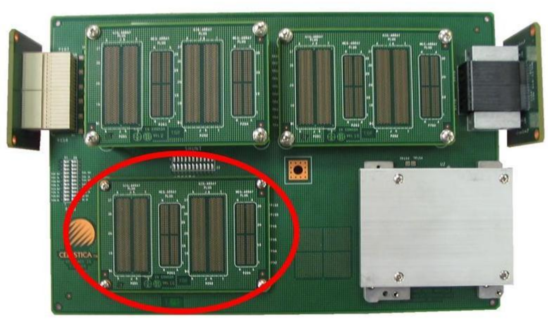

Figure 2 - "Metro" Test Vehicle

The motherboard for the "Metro" test vehicle was designed to comply with the requirements of IPC-9701, which was the current version of the specification at the time of the design. It was 8" x 12" and 0.093" thick, with 10 - 0.5 oz. copper layers. As IPC-9701 was not written with connectors in mind, it does not cover PCB design guidelines for daughter cards. It was decided to create a daughter card 3" x 4.5" in size and 0.062" thick, with 6 – 0.5 oz. metal layers, as this was thought to provide a reasonable simulation of a typical daughter card. The outer layers on both test vehicles were plated up to a total copper thickness equivalent to 1 oz. copper. Both boards were sourced in three different surface finishes – OSP, ImmAg and ENIG. The daughter card mated to the motherboard through two Mezzanine B connectors.

The "Metro2" test vehicle motherboard and daughter cards were both heavily based on the original "Metro" designs. Although the motherboard was the same size and thickness as the original "Metro" test vehicle, the layout was changed in order to evaluate the effect of design variables on the reliability of the Mezzanine B connector, and to incorporate some new connectors. As seen in Figure 3, three different variations of Mezzanine Connector B, all lead free, were used on the test vehicle. The three "Metro2" daughter cards dedicated to Mezzanine Connector B are labeled B through D. Daughter card C includes a version identical to what was used in the "Metro" test vehicle – a 4mm component stack height, with a 0.062" thick daughter card. This allowed a direct comparison to be made between the tin/lead and lead free versions of the component. Daughter card D uses the same 4mm stack height connectors, but increases the daughter card thickness to 0.093", while keeping the layer count constant at 6. This allowed the effect of daughter card thickness on the connector's reliability to be assessed. Finally, Daughter card B uses the same 0.093" thick daughter card as Daughter card D, but the connector stack height has been increased to 6mm. This allowed the impact of connector stack height on the reliability to be assessed. The surface finish for all "Metro2" test vehicles was OSP.

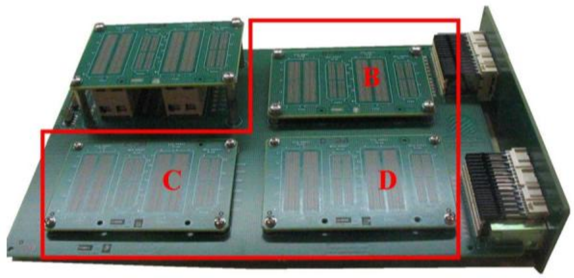

Figure 3 – "Metro2" Test Vehicle

Build Plan

The build plan for the "Metro" and "Metro2" test vehicles is shown in Table 1. The sample sizes generally conformed to IPC-9701A. The sample size for the OSP cell in the "Metro" test vehicle was reduced due to limitations in ATC chamber size, and no reworks were performed on that cell. For "Metro2", reworks were only performed on the 6mm stack height version of the connector. The height of the components is a significant factor affecting the difficultly of the rework, so only the most challenging component was reworked. Since no reworks were performed on the 4mm stack height connectors, the primary attach sample size was larger for those components in "Metro2".

Table 1 - Build Plan

Version	Primary Attach Connectors	Reworked Connectors
"Metro" Test Vehicle		
SnPb, 4mm stack, 0.062" Daughter card, OSP	10	0
SnPb, 4mm stack, 0.062" Daughter card, ImmAg	32	10
SnPb, 4mm stack, 0.062" Daughter card, ENIG	32	10
"Metro2" Test Vehicle		
SAC405, 6mm stack, 0.093" Daughter card, OSP	32	10
SAC405, 4mm stack, 0.062" Daughter card, OSP	44	0
SAC405, 4mm stack, 0.093" Daughter card, OSP	44	0

One issue which required some thought in reliability testing of connectors was the definition of a reworked location. Since these mezzanine connectors consist of two separate components, the plug and the receptacle, either or both sides of a mated pair could be reworked. For maximum ease in interpreting the results, a reworked location is defined in both projects as a connector where both mating halves have been reworked. Although this situation would be relatively rare in the field, it represents the worst case scenario, and guarantees that any failure of a reworked location is associated with a connector half that has been reworked, and cannot be attributed to a primary attach connector half mated to a reworked connector half.

Test Vehicle Assembly

All test vehicles were assembled using no-clean Sn3.8Ag0.7Cu solder paste. Three separate stencils were used in the assembly – one for the motherboard, one for the backplane, and one for the daughter card. The paste volume was measured using an automated paste inspection tool on a sample of boards during the build. The average paste volume for Mezzanine Connector B was 2810 mil^3 on the motherboard, and 2568 $mils^3$ on the daughter card. Paste height in both cases was approximately 7 mils.

Although placement can be a challenging process for some area array connectors due to their height and weight, placement of Mezzanine Connector B was not a significant challenge, as these particular connectors do not have a considerably higher profile than many common surface mounted components, and are not particularly heavy. Reflow profiling for these components was also not difficult even for these lead free assemblies, as they do not have an unusually high thermal mass. All of the cards were inspected using transmissive x-ray after assembly, and yield was 100% for all variations of Mezzanine Connector B. Ten plugs and ten receptacles were then subjected to forced rework. As the rework temperatures are quite high for the lead free rework process, care must be taken to shield the connector's plastic body adequately during the reflow process to prevent melting or blistering. Finer molded features in the plastic housing are especially vulnerable to this type of damage, but it was possible to shield the connectors adequately. All Mezzanine Connector B reworks passed x-ray inspection, but once mated, one of the ten reworked sites failed electrical test. As a result, a total of nine reworked samples were monitored during accelerated thermal cycling.

Time Zero Cross Sections

One finished assembly was set aside for time zero cross sections, which could be compared to the time zero cross sections from the original "Metro" test vehicle. Figure 4 shows a cross section of Mezzanine Connector B from the original "Metro" test vehicle. This photo illustrates the unusual structures used to connect the area array balls to the connector.

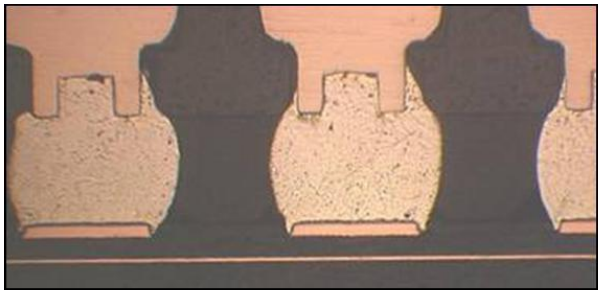

Figure 4 - Time Zero Cross Section of Tin/Lead Mezzanine B Connector

Figure 5 shows time zero cross sections from the lead free "Metro2" test vehicle. The photo on the left shows a similar view to that seen in Figure 4, showing that the connector's structure remains the same. The image on the right shows a magnified view of a single joint, showing the structure of the lead free joint prior to thermal cycling.

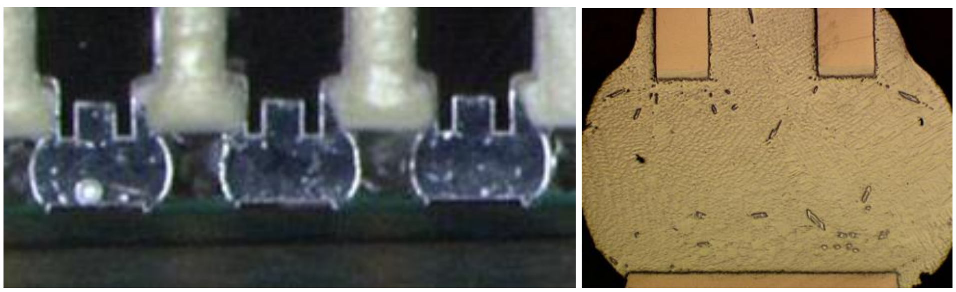

Figure 5 - Time Zero Cross Sections from Lead Free Mezzanine Connector B (Left – 25X, Right – 100X)

ATC Testing

A total of 22 "Metro2" assemblies were placed in a chamber for accelerated thermal cycling. The thermal cycling was conducted in accordance with IPC-9701A, and used the 0°C – 100°C profile, with 10 minute dwells at both temperature extremes. Figure 6 shows the customized fixtures which were created to hold the test vehicles in place, and to allow the airflow to circulate freely around the cards.

Figure 6 - "Metro2" Cards Mounted in a Rack for ATC Testing

A total of five similar racks were used to hold the test vehicles in the chamber, as shown in Figure 7. The test setup for the original "Metro" test vehicle was very similar – the profile in that case was also compliant with IPC-9701, and utilized similar racks for holding the test vehicles. The main difference between the two tests was that the ramp rate for the original "Metro" test was slower, as a larger chamber with lower ramping capability had to be used for that test due to the larger number of samples. In both cases, however, the ramp rates complied with IPC-9701.

Figure 7 - ATC Chamber Showing Layout of Racks

All test vehicles were fully in-situ monitored during testing using dataloggers. The failure criterion was a five consecutive readings showing a 20% or greater resistance increase over the resistance of the net measured during the hot dwell on the first cycle. Once failures were identified by the tester, the chamber was stopped periodically so the failures could be confirmed manually and the exact failing joints could be identified. This allows the early failure locations to be mapped to assist in identifying the mechanisms causing the failures, and to identify the locations to target for destructive failure analysis.

Results

A Weibull Plot showing the results of ATC testing of the original tin/lead "Metro" test vehicle is shown in Figure 8. The three curves shown represent the results for primary attach connectors on each of the three finishes studied. The results on all three finishes were quite comparable. The connectors had a characteristic life of approximately 1200 to 1400 cycles, with N1% values of approximately 400 to 600 cycles. Results for reworked connectors were generally quite comparable to the primary attach results.

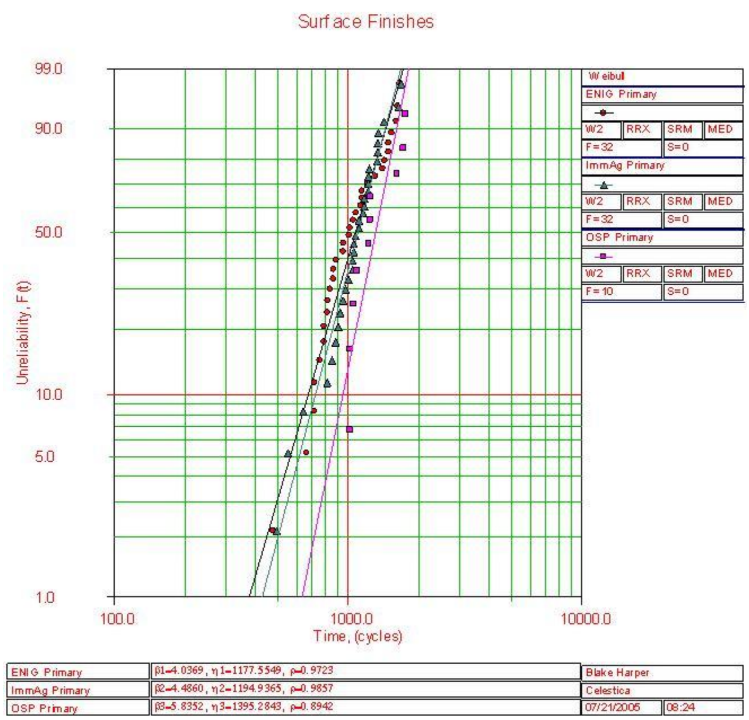

Figure 8 - Weibull Plot for Primary Attach Tin/Lead Mezzanine Connector B

As failures were identified by the in-situ monitoring equipment, they were electrically isolated using a multimeter. As electrical failure isolation cannot determine whether the failure is on the motherboard side or the daughter card side, two cross sections (receptacle and plug) were necessary to determine which half of the connector was affected and what the root cause of the failing site was. It was determined that the failure mode was solder fatigue cracks predominately located on the connector mounted to the daughter card. The cracks propagated through the bulk solder just above the intermetallic layer on the board side of the joint. A typical example is shown in Figure 9.

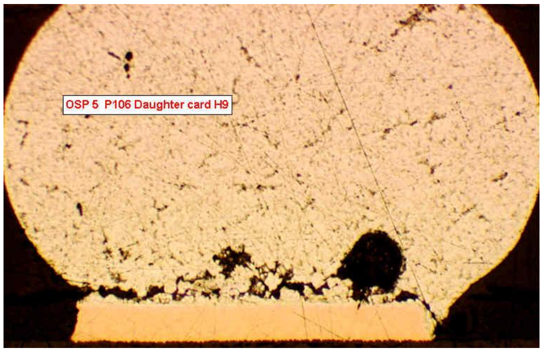

Figure 9 - Typical Fatigue Failure on Metro1, Daughter card Side

The location of the failures was mapped on diagrams of the daughter card for each of the surface finishes. Figure 10 shows the failure map for initial attach ENIG samples – the trends observed were similar for all three finishes. The diagrams show the number of times a pin was isolated as a failure. In many instances several connectors exhibited more than one failing ball when initially probed. As sample sizes were unequal on the two sites (P105 and P106) due to the use of several P106 sites for forced rework samples, only general trends in failures should be considered, not the actual number of failures. The diagram shows the P105 and P106 locations of Mezzanine Connector B relative to the outline of the daughter card.

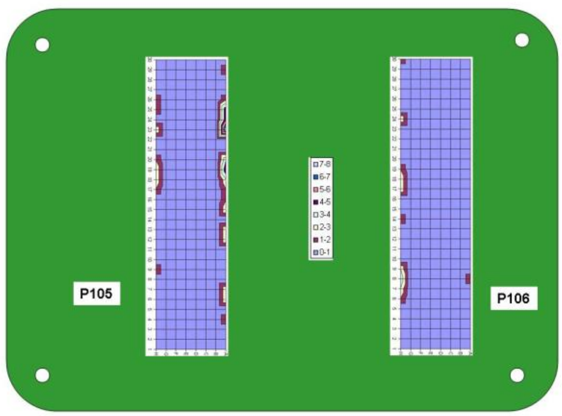

Figure 10 - Location Map of First Failures for Mezzanine Connector B on ENIG

The majority of the failures occurred along the inside long edge of the connector. One other observation from the map is that the majority of failures occurred in the center of the long edge of the connectors rather than near the corners as would be expected if the failure locations were strictly related to the distance from the neutral point. Similar plots were generated for the other surface finishes, and the finish did not appear to affect the location of the first failures, as would be expected. Similar trends were observed for the reworked cards.

To assist in understanding the reasons for the failure locations observed, the coefficient of thermal expansion of the connector was measured by Digital Speckle Correlation[5,6]. These measurements indicated that the CTE of the connector was different in each of the three directions. This variance was mainly due to the flow of the polymer material during the molding process. It was determined that the CTE in the x direction, which was measured close to the centre of the connector, was approximately 15ppm/°C, similar to that of the printed wiring board at 13-14 ppm/°C. In the y direction, the CTE of the connector was much higher, at 23-27 ppm/°C. With such a significant mismatch between the CTE of the connector in the y direction and the CTE of the board, the failures would tend to form along the long edges of the connector, as was observed in testing. Figure 11 shows part of an actual Metropolis test vehicle illustrating the Mezzanine B connectors with the referenced x and y directions highlighted.

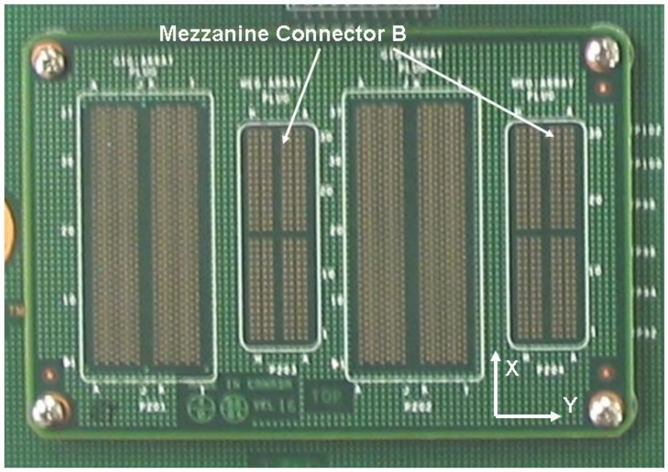

Figure 11 - Mezzanine Connector B Assembly Viewed from Above with Axes for CTE Measurements Marked

The CTE values measured in the Z direction were unexpectedly high – in the range of 84 to 97 ppm/°C. The CTE of stainless steel, the material used for the standoffs, was verified by literature to be 10-17 ppm/°C, depending on the grade. Figure 12 shows a simple diagram of the Mezzanine Connector B portion of the assembly in cross section. The relevant CTE values are shown for the various components of the system.

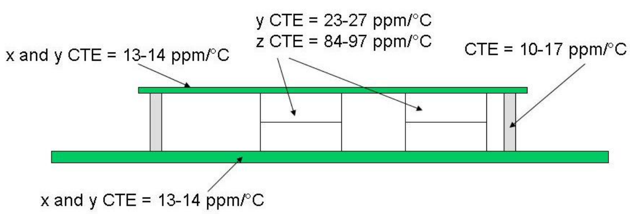

Figure 12 - CTE Values for Various Components of the Assembly

Based on these CTE values, the following failure is proposed. As the assembly is heated, the connectors begin to expand in the z-direction very quickly compared to the rest of the assembly. The standoffs also expand, but at not as much, due to their lower CTE. As a result of the difference in rates of expansion in the z direction, the daughter card begins to bow upwards (the daughter card is thinner than the motherboard). As the connectors continue to expand, and a tensile stress is created in the card. Simultaneously, the daughter card, motherboard, and connectors expand in the x- and y- directions. These key movements are shown in Figure 13.

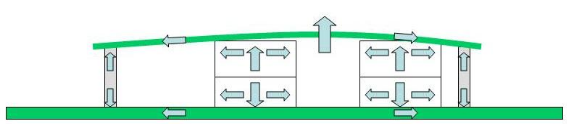

Figure 13 - Key Movements Contributing to Failures

With such a large tensile stresses applied repeatedly to the solder joint on the daughter card side of the connector as a result of thermal cycling, solder joint fatigue commences. Figure 14 shows a simplified diagram of one half of the daughter card showing the key stresses on the solder joints. A tensile stress is generated through the daughter card as described, and is represented by the large arrows above the card in this figure. As the connector CTE in the y-direction exceeds the CTE of the board, the connector will expand at a greater rate than the board. The resultant stress is represented by the smaller arrows in the connector body.

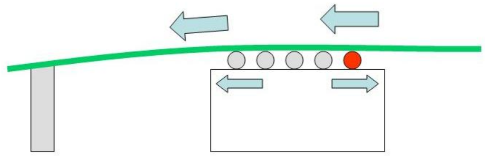

Figure 14 - Summary of Key Stresses on Daughter Card Solder Joints

The result is that on the outside row of balls (closest to the standoff), the tensile stress in the card and the stress from the expansion of the connector act in the same direction, and the solder joint experiences a relatively lower strain. On the inner row (represented by the red solder joint), the tensile stress in the card and the stress from the expansion of the connector relative to the board act in opposite directions, resulting in a higher strain on the solder joint. As a result, the inner rows of balls would tend to fail first, which is what was seen in the ATC results.

At the time of writing, over 2600 cycles of ATC were complete on the lead free Metro2 test vehicles. No failures have been observed on any of the components in the chamber. In previous projects, tin/lead and lead free versions of otherwise identical BGA packages have been tested in 0°C to 100°C thermal cycling. In those instances, the lead free versions of the package outperformed the tin/lead versions by approximately 2 to 2.3X[7]. While there are substantial differences in the construction of a BGA package as compared to a connector, this may be considered an estimate for the expected difference in performance between the 4mm stack height Mezzanine Connector B with lead free balls and the tin/lead version. The characteristic life of this connector on an OSP board was 1395 cycles on the tin/lead test vehicle – this corresponds to a projected characteristic life of approximately 2800 to 3200 cycles. Failures would therefore be expected to occur very shortly if the correlation between the performance of tin/lead and lead free balled components holds true for the area array connectors.

As there are not yet any failures, it is not possible to determine whether changing the connector's stack height or changing the thickness of the daughter card affects the reliability. It will be necessary to wait for failures to occur to evaluate the effects of the design changes.

Design Considerations for Area Array Connectors

The results of the tin/lead testing indicate that many things may play a role in the location of the failures, and potentially, also the timing of the failures. Careful consideration must be given to the thickness of the motherboard and daughter card, as well as to the material of any standoffs. The position of the connectors relative to each other is also expected to have an impact – placing them end-to-end rather than side by side as was done in the Metro and Metro2 cards may have a dramatic impact on failure locations. As a greater amount of data is generated on area array connectors, it will be possible to determine the magnitude of the effect of these design parameters on the reliability of the connectors, and to develop guidelines for the most reliable way to design in these connectors.

Conclusions

The performance of the lead free connectors was excellent in 0°C to 100°C thermal cycling, outperforming their tin/lead equivalents by at least a factor of 1.85X. No lead free failures have been observed by 2600 cycles of ATC, though failures are expected to begin to occur very shortly based on tin/lead to lead free correlation factors determined using conventional BGA packages.

The absence of failures prevents conclusions at this time regarding the effect of the design parameter changes on the reliability of the connector. Thermal cycling will continue to 6000 cycles, by which time sufficient failures are expected to have accumulated to allow the effect of the design changes on the reliability and/or failure mode to be determined.

Future Work

Future work for this project will focus primarily on completing 6000 cycles of ATC testing, and analyzing any failures that occur. The failure modes and cycles to fail will be compared to the results of the original "Metro" test to determine if there are any differences.

Additional work is also underway to look at the impact of repeated mating and unmating on the reliability of the connectors. A new set of test vehicles is currently undergoing controlled mating and unmating for a total of 25 mating cycles for mezzanine connectors, and 50 cycles for the backplane connectors. At the conclusion of the mating and unmating, the test vehicles will be placed into ATC using the 0°C to 100°C profile to determine if there is any impact on the reliability of the connectors.

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